espp2026-ppg-strong_int@cern.ch

European Strategy for Particle Physics

Strong Interactions WG

Parallel session

23 June 2025

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Group structure: physics areas and experts

Conveners: Andrea Dainese (EXP, IT), Cristinel Diaconu (EXP, FR)

Scientific Secretary: Chiara Signorile-Signorile (TH, DE)

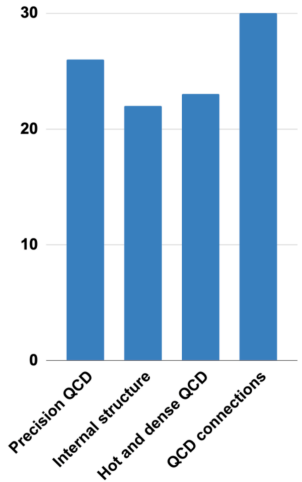
- **Precision QCD**
  - Physics: elementary processes, alpha_S, fragmentation, hadronization, photon-photon
  - Machines: HL-LHC, FCC-ee, other lepton collider options, FCC-hh
  - *David d'Enterria (EXP, CERN), Sven Olaf Moch (TH, DE)*
- **Internal structure of protons and nuclei**
  - Physics: PDFs and nuclear PDFs, gluon saturation, proton spin
  - Machines: HL-LHC, EIC, LHeC, FCC-eh, FCC-hh, Muon Collider
  - *Nestor Armesto (TH, ES), Andy Buckley (EXP, UK)*
- **Hot and dense QCD**
  - Physics: Heavy ions, Quark-gluon plasma, Collectivity in QCD
  - Machines: HL-LHC, SPS, FAIR, FCC-hh / ions
  - *Roberta Arnaldi (EXP, IT), Raimond Snellings (EXP, NL), Urs Wiedemann (TH, CERN)*
- **QCD connections with hadronic, nuclear and astro(particle)physics**
  - Physics: hadron spectroscopy and exotica, hadron-hadron strong interaction, QCD in cosmic-ray physics (incl. DM searches), QCD in neutron star cores, QCD in nuclear structure
  - Machines: HL-LHC, SPS, FAIR
  - *Antoine Gérardin (TH, lattice, FR), Valentina Mantovani Sarti (EXP, DE), Marco Pappagallo (EXP, IT)*

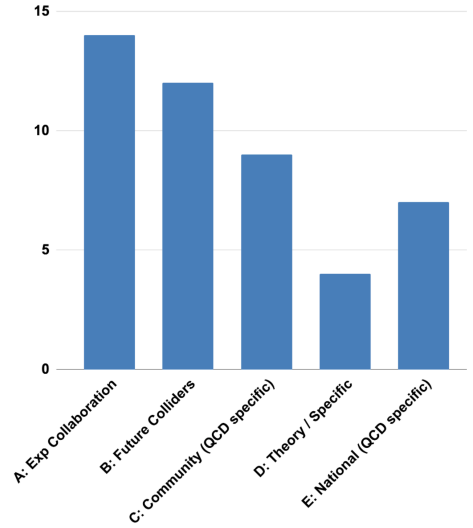
European Strategy Update 2026: timeline

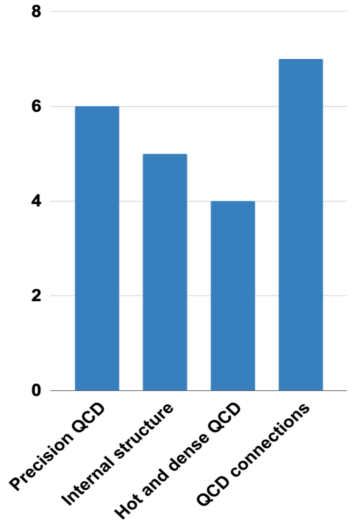
Submitted Input Documents mapped to Strong Interactions WG

- **47 input documents (35 for ESPPU 2020)**
  - All physics areas identified in 2020 are covered, in general more documents per area
  - Most of them from large collaborations and experiments
  - In general, little input from theory (despite our communication campaigns) → direct contacts ongoing with several groups

- **Analysis of the inputs by WG**
  - Inputs have been assigned to subareas
  - Relevant comments to the inputs and benchmarks have been “extracted” from the documents
  - Inputs have been complemented by the material already collected by the WG







Submitted Input Documents - Overview

Tables with links to inputs

Experimental Collaborations			Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl, astr)
6	Input for the EUROPEAN STRATEGY FOR PARTICLE PHYSICS UPDATE 2026 compiled by THE ISOLDE COLLABORATION COMMITTEE	ISOLDE				X
205	The Belle II Experiment at SuperKEKB	KEK Belle II	X			X
68	Input from the ALICE Collaboration	LHC ALICE		X	X	X
170	Highlights of the HL-LHC physics projections by ATLAS and CMS	LHC ATLAS+CMS	X	X		
23	Prospects and Opportunities with an upgraded FASER Neutrino Detector during the HL-LHC era: Input to the EPPSU	LHC FASER		X		X
19	The Forward Physics Facility at the Large Hadron Collider	LHC FPF		X		X
81	Discovery potential of LHCb Upgrade II	LHC LHCb				X
82	Heavy ion physics with LHCb Upgrade II	LHC LHCb		X	X	X
213	LHCspin: a Polarized Gas Target for LHC	LHC LHCspin		X		
245	MUonE Contribution to the European Strategy: status of the project	mu CERN MUonE	X			
131	European Strategy for Particle Physics 2026: the NA60+/DiCE experiment at the SPS	SPS NA60+/DiCE			X	
171	Proposal from the NA61/SHINE Collaboration for the update of the European Strategy for Particle Physics	SPS NA61/SHINE			X	X
231	Super Tau Charm Facility	STCF China	X			X

Submitted Input Documents - Overview

European Strategy for Particle Physics

Future Colliders			Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)
114	Synergies between a U.S.-based Electron-Ion Collider and European Research in Particle Physics	eh: EIC USA	X	X		
214	The Large Hadron electron Collider (LHeC) as a bridge project for CERN	eh: LHeC	X	X		
209	FCC: QCD physics	FCC	X	X	X	X
227	Prospects for physics at FCC-hh	FCC	X	X	X	X
233	FCC Integrated Programme Stage 1: The FCC-ee	FCC	X			
241	The FCC integrated programme: a physics manifesto	FCC	X	X	X	X
247	FCC Integrated Programme Stage 2: The FCC-hh	FCC	X	X	X	X
141	The ECFA Higgs/Electroweak/Top Factory Study	FCC/LC/CLIC/MuCol	X			
275	Status of the International Linear Collider	ILC	X			
188	LEP3: A High-Luminosity e+e− Higgs & Electroweak Factory in the LHC Tunnel	LEP3	X			
152	United States Muon Collider Community White Paper for the European Strategy for Particle Physics Update	Muon Collider		X		
207	The Muon Collider	Muon Collider		X		

Submitted Input Documents - Overview

Community (QCD specific)			Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)
224	Community Support for Physics with high-luminosity proton-nucleus collisions at the LHC	HI at HL-LHC		X	X	X
2	Light Ion Collisions at the LHC	HI Light ions LHC		X	X	X
7	Conclusions of the Town Meeting: Heavy Ion and QGP Physics at CERN	HI physics CERN			X	
55	Kaon Physics: A Cornerstone for Future Discoveries	Kaon Phyiscs				X
29	Strategy for the Future of Lattice QCD	Lattice QCD		X	X	X
103	Nuclear Physics and the European Particle Physics Strategy Update 2026	NuPECC		X	X	X
235	Summary Report of the Physics Beyond Colliders Study at CERN	Phyiscs Beyond Colliders	X	X	X	X
89	Precision cross-sections for advancing cosmic-ray physics	Cross sections for cosmics	.			X
201	Statement of the Pierre Auger Collaboration as input for the 2026 European Particle Physics Strategy	HI for cosmics (AUGER)	.			X
Theory / Specific						
174	Phase-One LHeC	Personal input LHeC/HL-LHC	X	X		
33	Computer Algebra for Precision Calculations in Particle Physics: the FORM project	QCD theory/computing	X			
35	Cusp Spectroscopy, Hyperon-Nucleon Scattering, and Femtoscopy: Pioneering Tools for Next-Generation Hadron Interaction Studies	QCD theory/computing	.			X
113	Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics	Quantum Computing	X			X

Submitted Input Documents - Overview

National (QCD specific)			Precision QCD	Internal structure	Hot and dense QCD	Connections (hadr,nucl,astr)
5	Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 and beyond and future colliders at CERN	France QCD	X	X	X	
126	Input to ESPPU by the German Astroparticle Community	Germany Astroparticle	.			X
183	Input of the German Nuclear and Hadron Physics Community to the ESPPU 2026 Regarding the Programs at CERN, at FAIR, and Related Activities	Germany Hadronic and Nuclear	.		X	X
117	The INFN National Scientific Committee for Theoretical Physics	Italy Theory	X		X	X
51	Ultra-relativistic Heavy-Ion Collisions: Inputs of the Italian community for the ESPP 2026	Italy HI	.		X	
76	Input on the update of the European Strategy for Particle Physics by the INFN Nuclear and Hadron Phyiscs Community	Italy Nuclear Phys	.		X	X
246	U.S. interest in high-energy nuclear physics at the LHC	US LHC HI community	.		X	

Benchmark measurements (more details)

European Strategy for Particle Physics

Note: this is not an exclusive list of the observables and measurements that the working group will cover.

- Precision QCD
  - Strong coupling α_S and its Q^2 dependence;
  - Strong interaction effects on top and W masses;
- Internal structure of protons and nuclei
  - Longitudinal and transverse proton PDF(x,Q^2);
  - Longitudinal and transverse nuclear PDF(x,Q^2);
- Hot and dense QCD
  - Heavy-flavour hadron production (rare states, kinematic coverage);
  - QGP thermal radiation / temperature;
- QCD connections with hadronic, nuclear and astro(particle) physics
  - Constraints on nature of exotic hadrons from spectroscopy and h-h correlations;
  - Precision on anti-nuclei production and absorption relevant for cosmic-ray physics;

Facility, Experiments	Colliding systems, c.m.s. energy	Timeline	Precision QCD	Partonic dynamics in protons and nucleons	Hot and dense QCD	QCD connections (hadronic, nuclear, astrophysics)
HL-LHC: ALICE 3, ATLAS & CMS pII, LHCb U2, LHCspin	pp 14 TeV AA 5.5 TeV pA 8.8 TeV	> 2035 (ALICE 3, LHCb U2)	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, m_W	(n)PDF, TMD, small x, intrinsic charm	Precision charm, beauty, hard and e.m. probes, μ_B=0; time evolution	Hadr. int., (hyper/charm)nuclei, Exotica, Cosmic antinuclei, Neutron Star EoS
HL-LHC: FPF	LHC collisions, neutrino-nucleon	> 2031		(n)PDF, small x, intrinsic charm		Cosmic rays (neutrinos)
SPS: NA60+, NA61	pA, AA, 6-17 GeV	> 2030 (NA60+)		nPDF, medium/large x	Charm, dileptons, critical point?, μ_B=200-450MeV	Cosmic anti-nuclei, neutrinos
FAIR SIS-100: CBM	pA, AA, 2.5-5 GeV	> 2028			Hadrons, dilept., critical point?, μ_B =500-700MeV	(Hyper)nuclei
MUonE	μ(160 GeV)-e	> 2030	g-2 (hadronic)			
HIE-ISOLDE upgrades	Radioactive ion beams	> 2029				Nucl. phys. Inputs NS EoS
KEK: Belle II upg.	ee 10 GeV	> 2035	$\alpha_s(m_\tau^2)$			Exotica (c,b)
STCF	ee 2-7 GeV	> 2033	$\alpha_s(m_\tau^2)$			Exotica (c)
EIC	ep, eA 28-140 GeV	> 2036	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, medium/large x		Exotica (c,b)
LHeC	ep, eA 1.2 TeV	> 2043	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	(n)PDF, TMD, GPD, small to large x		Exotica (c,b)
FCC	ee 90-365 GeV pp 85 TeV AA 33.5 TeV pA 53.4 TeV	> 2047 > 2074	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W	(n)PDF, TMD, small to large x	New probes of time evolution, early times, μ_B=0	Cosmic rays (modeling primary interaction)
LCF CLIC	ee 0.25-1 TeV ee 0.38-1.5 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$, m_t, Γ_t, m_W			
LEP3	ee 91-230 GeV	> 2047	$\alpha_s(m_Z^2)$			
Muon Collider	$\mu\mu$ 3-10 TeV	> 2050	$\alpha_s(m_Z^2)$, $\alpha_s(Q^2)$	PDF using sec. neutrino beam		

European Strategy Update 2026: timeline

Preparation: Open Meetings

European Strategy for Particle Physics

ESPP2026 - Strong Interactions Open WG Meetings

14 May 2025, 13:30 → 28 May 2025, 15:00 Europe/Zurich

ZOOM only

~40 participants

Open WG meeting 14 May

https://indico.cern.ch/event/1527574/

Hot and dense QCD (R. Arnaldi, R. Snellings, U. Wiedemann)

- Heavy flavour probes of the quark-gluon plasma: goals and benchmarks (David Dobrigkeit Chinellato)
- Thermal radiation from the quark-gluon plasma: goals and benchmarks (Gianluca Usai)
- Jets and quark-gluon plasma inner structure: goals and benchmarks (Jasmine Brewer)

Internal structure of protons and nuclei (N. Armesto, A. Buckley)

- Collinear proton PDFs (Tom Cridge, Claire Gwenlan, Maria Ubiali)
- Nuclear PDFs in view of future facilities (Hannu Paukkunen)
- Overview of TMD physics at colliders (Valerio Bertone)

Preparation: Open Meetings

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Open WG meeting 28 May

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Precision QCD (D. d'Enterria, S.-O. Moch)

- QCD at FCC-ee (Pier Monni)
- Precision QCD at LHeC (Daniel Britzger)
- Precision QCD with Belle-II (Anselm Vossen)
- α_S extraction at EIC (Win Lin, Zuhal Demiroglu, Abhay Deshpande)
- QCD at next-generation e^+e^- colliders (Michael Peskin)

QCD connections (A. Gérandin, V. Mantovani Sarti, M. Pappagallo)

- Precision cross-section measurements for cosmic rays physics (Fiorenza Donato)
- Recent progress and open challenges for hadron spectroscopy and exotic states from lattice QCD (David Wilson)
- Tightly-bound multiquarks vs hadronic molecules (Marek Karliner)

European Strategy Update 2026: timeline

European Strategy for Particle Physics

Introduction: Strong Interactions WG and ESPP inputs — *Chiara Signorile-Signorile (Max Planck Institute for Physics)*
Palazzo del Casinò, Sala Mosaici 1 11:15 - 11:30

Precision QCD: state-of-the-art and prospects with future facilities — *David d'Enterria (CERN)*
12:00
Palazzo del Casinò, Sala Mosaici 1 11:30 - 12:15

QCD input to cosmic rays and compact stellar objects: open questions and next challenges
Valentina Mantovani Sarti (TUM)

Prospects for exotic hadron physics — *Antoine Gerardin (AIX-Marseille University) et al.*
Palazzo del Casinò, Sala Mosaici 1 12:37 - 13:00

13:00 **Lunch Break**
Palazzo del Casinò, Sala degli Specchi 13:00 - 14:00

14:00 **Partonic dynamics in protons and nuclei: prospects with future measurements at HL-LHC and electron-hadron colliders**
Néstor Armesto (IGFAE-Compostela Univ.)
Palazzo del Casinò, Sala Mosaici 1 14:00 - 14:45

Hot and dense QCD: future prospects in heavy-ion collisions — *Urs Wiedemann Wiedemann (CERN)*
15:00
Palazzo del Casinò, Sala Mosaici 1 14:45 - 15:30

Short Break to allow for change rooms
Palazzo del Casinò, Venice Lido 15:30 - 15:40

Today: time for discussion included
(15' for each physics area)

Wednesday 25/06, 11:15

Open questions and experimental prospects: precision QCD & internal structure of protons and nuclei
Cristinel Diaconu (CPPM)

Open questions and experimental prospects: hot and dense QCD & QCD connections to hadronic, nuclear and astrophysics
12:00
Andrea Dainese (INFN-Padua)

Discussion — *Sven-Olaf Moch (University of Hamburg) - discussion leader*
Sala Perla, Palazzo del Casinò 12:15 - 13:00

European Strategy
for Particle Physics

Thanks for your attention!

Benchmark measurements

European Strategy for Particle Physics

2 Strong Interactions

The benchmark measurements in the area of the strong interaction are reported in the following for the four main physics research directions. Clearly, this is not an exclusive list of the observables and measurements that the working group will cover. The input documents are anticipated to have a much broader coverage, which will be taken into account. The list of benchmarks will be used to summarise and highlight the complementarity and strengths of the future measurements at existing (e.g. SPS, HL-LHC) and proposed colliders (leptonic, hadronic, electron–hadron). The presentation of results will be organised by the working group in communication with the contact persons of submitted inputs.

- Precision QCD
  - $\alpha_S(m_Z)$ and its Q^2 dependence;
  - Strong interaction effects for precision measurements of top and W masses (see comments at the end of the section);
    - Comment on top and W masses: while these are formally EW parameters, the strong-interaction aspects are important for their experimental and theoretical determination. For example, we propose to report the expected experimental performance for the following approaches to t and W mass measurements.
      - ee collisions: m_t from threshold scan around $\sqrt{s} = 340$ GeV; m_W from threshold scan for W^+W^- production (leptonic decays);
      - ep collisions: m_t from heavy-quark DIS (top-quark structure function measurements); m_W from inclusive DIS (charged-current structure function measurements);
      - pp collisions: m_t from $t\bar{t}$ production rates, multi-differential in $m_{t\bar{t}}, y_{t\bar{t}}$; m_W from p_T^ℓ distributions.
- Inner structure of protons and nuclei
  - Longitudinal and transverse proton PDF(x, Q^2): parton flavours, Bjorken-x and Q^2 ranges for which new constraints and reduction of uncertainties are expected;
  - Longitudinal and transverse nuclear PDF(x, Q^2); same as above;
- Hot and dense QCD
  - Heavy-flavour and quarkonium hadron production (rare states, kinematic coverage): expected novel access to low-cross-section open and hidden heavy-flavour hadrons, multi-differential observables (such as correlations), transverse momentum and rapidity ranges;
  - QGP transport coefficients (heavy quarks, jets): expected precision for observables that constrain the transport coefficients that characterise parton energy loss and heavy-quark interactions in the QGP;
  - QGP thermal radiation, sensitivity to temperature: expected precision for measurements of thermal radiation and parameters that map to the temperature of the hot and dense system formed in heavy-ion collisions at different centre-of-mass energies and regions of the QCD phase diagram;
- QCD connections with hadronic, nuclear and astro(particle) physics
  - Constraints on nature of exotic hadrons from spectroscopy and h-h correlations; expected measurements that can help understanding the structure of exotic heavy-flavour hadrons (e.g. compact tetraquark vs. hadron molecule), including direct measurements of yields, resonant states, kinematic distributions in different collision systems, and hadron-hadron momentum correlation functions that have sensitivity to bound states;
  - Precision on anti-nuclei production and absorption relevant for cosmic-ray physics: production of light anti-nuclei (e.g. $\bar{p}$, $\bar{d}$, $^3\bar{H}e$) that constrain production processes and kinematic distributions in primary cosmic-ray interactions; annihilation cross sections for anti-nuclei on nuclei, relevant for the propagation of cosmic anti-nuclei in space (e.g. from Dark Matter decays);

2019 inputs on Strong Interaction

European Strategy for Particle Physics

Category: Facilities and experiments with strong interactions as key topic
(Id13) NA61++ (SPS)
(Id42) PBC@CERN, COMPASS++, MUSE@PSI, MUonE, DIRAC++, NA61++
(Id46) Heavy flavour in HI
(Id47 and Id67 and Id110) LHC-FT: ALICE and LHCb (LHCSpin)
(Id90) NA60+ (SPS)
(Id110) ALICE upgrade for HL-LHC
(Id135) QCD/HI at FCC-hh and FCC-eh
(Id143) COMPASS++/AMBER (SPS)
(Id152) QCD/HI at HL-LHC
(Id159) LHeC/PERLE
(Id160) QCD/HI at HE-LHC

Category: Synergies on a global scale
(Id76) J-PARC
(Id93) NICA
(Id99) US-based EIC

Category: Facilities & experiments with strong interactions as a topic
(Id13 and Id50) AWAKE
(Id49) Super Charm-Tau Factory

Category: QCD results in support for other programs
(Id117) Auger experiment
(Id131) LBNF/DUNE
(Id151) New physics with HI collisions

Category: QCD theory in support
(Id100 and Id101) Precise calculations @ colliders
(Id114) MC generators
(Id163) QCD theory

Category: QCD and nuclear physics
(Id39) ISOLDE/EPIC

Category: National roadmaps
(Id21) INFN Hadron
(Id37) Germany ALICE
(Id56) INFN HI
(Id115) Germany Hadron

Category: Individual and community thoughts
(Id48) Town meeting on Heavy Ions
(Id103) DIS
(Id140) personal input
(Id148) NuPECC